TITLE: **Fiber Orientation Effect on Dynamic Mechanical and Ballistic Properties of Spectrashield® Composites**

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ABSTRACT: The effect of fiber orientation in ultra-high strength Spectra® polyethylene fiber-reinforced composites was examined through the correlation of dynamic mechanical properties to the ballistic impact resistance efficiency of those composites. Spectra® fabric-based composites and Spectrashield® angle-plied laminates were included in the study. Based on the findings of this evaluation, fiber orientation significantly affected the flexural moduli and damping properties measured at the glass transition temperature (T_g) of polyethylene and at room temperature. Among the Spectrashield® angle-plied composites examined, the [0/±60] laminate showed the highest ballistic resistance capability, marginally ahead of the [0/90] samples.

At very low areal density, all Spectra®-based composite systems demonstrated similar ballistic limits. However, at higher areal densities, the Spectrashield® angle-plied materials surpassed the performance levels of the fabric-based composites. In both composite systems, the ballistic impact resistance efficiency reduced as areal density increased. The rate of reduction was more severe in the fabric-based composites than in the Spectrashield® angle-plied laminates.

An energy dissipation factor, η, obtained from the relationship of flexural storage and flexural loss moduli at the T_g of polyethylene (-125 °C) showed reasonably good agreement with ballistic kinetic energy absorption efficiencies for each laminate. This suggested that the low temperature transition (γ-transition) which is the T_g of polyethylene is an important parameter contributing to the high toughness and excellent ballistic impact resistance of the Spectra® composites.

Through optical and scanning electron microscopy, multiple modes of failure resulting from the ballistic impact event were identified in the Spectra® composites. Variations in the delamination at the impact point were observed in the two composite systems. Additional differences were also seen, not only between the fabric-based system and the angle-plied laminates but also between the angle-plied materials due to fiber orientation or ply layup.

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INTRODUCTION

Because of its excellent mechanical properties and low density, Spectra®, an ultra-high molecular weight polyethylene fiber commercially available from Allied-Signal, Inc., is a high-potential candidate for ballistic protective applications. Research and development is ongoing both at U.S. Army Natick Research, Development and Engineering Center (Natick) and in the private sector to optimize the ballistic-resistance capabilities of this high-strength fiber.

Traditionally, ballistic protection offered to the individual soldier in personnel armor is accomplished through the use of orthogonally woven fabric and fabric-based composites. In an attempt to exploit the outstanding properties of the Spectra® fiber, Allied developed a new composite technology identified by U.S. Patent No. 4,748,064.[1] The technology consists of a fibrous nonwoven-type material with polymer-impregnated Spectra® fibers formed into a unidirectional web.[2] Allied registered this technology as Spectrashield®. The Spectrashield® materials can be formed into soft armor systems, much like woven fabrics, or multiple layers of the Spectrashield® material may be molded to form composites.

Recent studies indicate that orthogonally stacked Spectrashield® unidirectional laminates show better ballistic impact resistance than orthogonally woven fabric-based composites.[2,3] With the Spectrashield® material, it is possible to alter the fiber orientation from the typical 0/90 degrees found in many fabric-based composites. Altering the fiber orientation of laminates with Spectrashield® unidirectional material produces a structural element capable of resisting load in several directions. The stiffness and damping properties of such a composite configuration are important parameters since both directly affect penetration resistance as well as deformation upon ballistic impact.

When a viscoelastic material is subjected to high frequency or high strain rates, such as a ballistic impact event, the material displays substantial stiffness, which resembles the behavior of polymeric materials at low temperatures. That is, the damping behavior associated with the amorphous region in a viscoelastic material appears negligible at low temperature or at high strain rates; thus the material behaves as if it were a glassy solid. For this reason, upon ballistic impact, its ability to elongate will be reduced and the amount of energy absorbed mainly depends on the stiffness of the polymeric material.

On the other hand, ultra-high molecular weight polyethylene has, in addition to high tensile strength and modulus, damping behavior observable at approximately -125°C. This low temperature is identified as the glass transition temperature (T_g) associated with its amorphous relaxation, which indicates that upon ballistic impact, polyethylene has the capacity to strain and the potential for amorphous reorientation.[4-8] This indication suggests that ultra-high modulus polyethylene has the capability for good ballistic impact resistance.[3,9,10]

Although some preliminary work has been completed on angle-ply effects during the developmental stage of Spectrashield®, limited information is available on this material. In this study, an analysis of fiber orientation effects on dynamic mechanical properties of Spectrashield® laminates is undertaken to assist in better understanding the failure and energy absorption mechanisms demonstrated upon ballistic impact. The damping properties of Spectrashield® laminates with various angle-plied configurations are examined in an attempt to show the correlation between these properties and ballistic impact resistance. The paper focuses on the work completed to date in assessing that relationship.

EXPERIMENTAL

TEST SAMPLES

Materials

The unidirectional Spectrashield® base material used in this study was obtained from Allied Signal, Inc., Morristown, New Jersey and was based on the Spectra® 1000 fiber. The resin matrix for the Spectrashield® prepreg consisted of a one-phase vinyl ester and polyurethane blend. The resin content represented approximately 25% by weight.

The second Spectra® based prepreg included in this analysis consisted of a Spectra® 900, 21 x 21 plain weave fabric with a two-phase vinyl ester and polyurethane resin system. The resin add-on of this system was also approximately 25% by weight.

Molding of Laminates

Five angle-plied laminate configurations with varying angle components were fabricated from the Spectrashield® unidirectional-base materials. Due to difficulties incurred in handling the Spectrashield® product, two layers of the unidirectional prepreg were combined and treated as one layer. For example, the actual construction of a [0/90] sample was $[0_2/90_2]$. In an effort to equalize areal densities as closely as possible and to eliminate data collection difficulties, the final laminate configurations examined in the study included $[0]_4$, $[0/90]_2$, [0/±45/90], [0/±30/±60/90], and [0±60].

The Spectra®fabric-based composites samples were assembled by layering single plies of the fabric prepregs in a manner to ensure that the yarn orientation was approximately biaxial (0/90 degrees). The biaxial orientation was represented by one-ply (each direction) and two-ply (alternating directions) configurations in the fabric-based laminates. Those samples were identified as $[0/90]_{F1}$ and $[0/90]_{F2}$, respectively.

All laminates were prepared by molding the prepregs in a hydraulic press with 6.9×10^6 Pa (1000 psi) pressure for 30 minutes at 120 ± 3°C. One-foot square samples were used in the ballistic evaluation. Appropriate-sized samples for the dynamic mechanical analysis were also constructed as described above.

EVALUATION PROCEDURES

Dynamic Mechanical Analysis

A DuPont Dynamic Mechanical Analyzer (DMA-983) was used to observe the effect of the fiber orientation on the dynamic mechanical properties of the laminates, especially, at low temperature. All samples were measured using low mass clamps at a fixed frequency of 1 Hz with oscillation amplitude of 0.5 mm and 2°C/min heating rate. Dynamic mechanical measurements were made in several different directions i.e. $(\pm 45)_4$, (±30/90).

Ballistic Evaluation

Kinetic energy absorption during the ballistic penetration was measured using the high speed impact apparatus located at Natick.[11] All low areal density samples were impacted at velocities of approximately 300 m/s. The sample holder used for the low areal density sample evaluation was that described by Song and Allen.[11] Data collected at the higher areal densities was in accordance with Military Standard, MIL-STD-662E, V_{50} Ballistic Test For Armor.[13]

Assuming the projectile mass was constant during the penetration of the laminated target, kinetic energy (KE) absorbed by the laminate is:

$$KE = 1/2\, m(V_s^2 - V_r^2) \tag{1}$$

where KE is kinetic energy (J), m is projectile mass (Kg), V_s and V_r are striking and residual velocities (m/s) respectively.

In this study, the ballistic limit (BL) is considered to be the single highest striking velocity where the residual velocity equals zero and can be estimated with:[12]

$$BL = (2KE/m)^{1/2} \tag{2}$$

Failure Mechanism Analysis

Scanning electron microscopy was used to observe the mode of failure resulting from the ballistic impact event. Small pieces (ca. 13 mm x 13 mm) of impacted laminates were mounted on specimen studs. The samples were coated in a sputter coater with a thin layer of gold palladium. The fracture patterns of the coated samples were examined in an AMRAY Model 1000A Scanning Electron Microscope using the secondary electron mode.

RESULTS AND DISCUSSION

DYNAMIC MECHANICAL ANALYSIS

Typical dynamic mechanical properties obtained during this study are represented by the plot shown in Figure 1. Four transitions are apparent. The transitions at near +140°C, +75°C, and -125°C are α', α and γ–transitions of polyethylene, respectively.[4] The α' and α-transitions are associated with motion within the crystalline regions whereas the γ transition is associated with the amorphous region hence the glass transition in the noncrystalline regions of polyethylene. The transition seen between -75°C and 0°C is considered to be the glass transition region of the polyurethane (resin matrix).[14]

The effect of fiber orientation on the flexural storage modulus (E') of the materials evaluated are shown in Table 1 and Figure 2. As indicated, the flexural storage moduli at low temperatures (T_g) are significantly higher than those at room temperature (20 °C). The laminates with more fibers aligned along the test direction demonstrated higher flexural storage modulus than the laminated samples with fibers aligned at angles to and away from the testing direction. For example, the $[0]_4$ sample which had all four (4) component fibers aligned in the test direction showed the highest values for flexural storage modulus; whereas the $[0/90]_2$ laminate with only two (2) components aligned in the test direction gave the second highest value. Those samples are followed, in descending order, by the configurations [0/±45/90], [0/±60], [0/±30/±60/90].

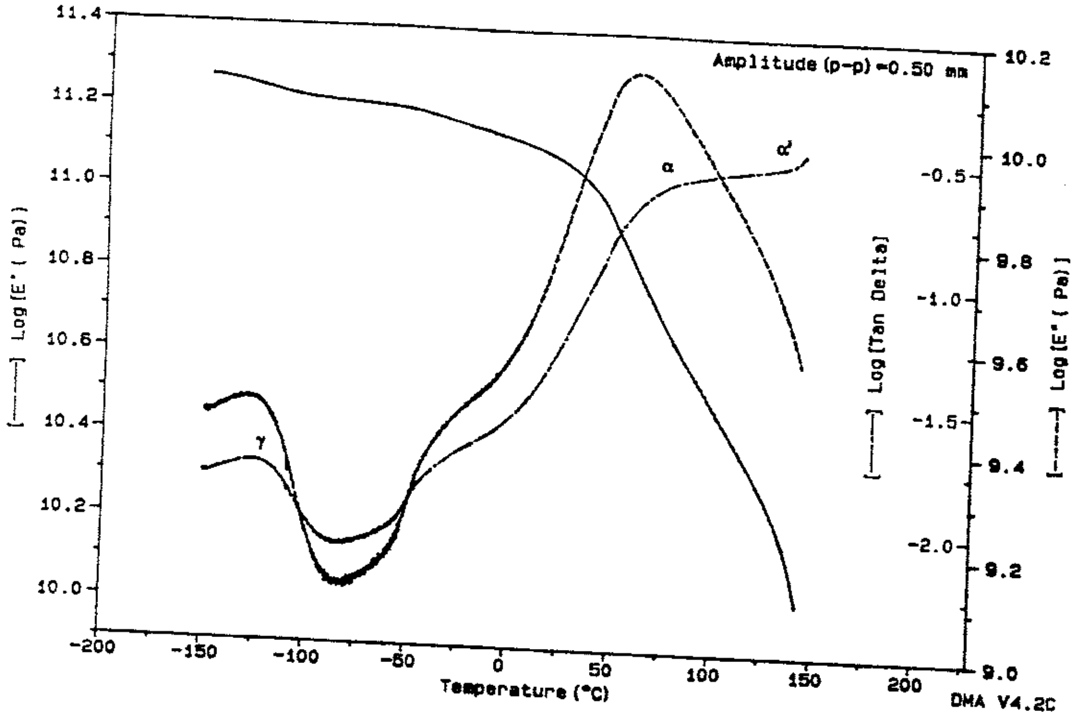


Figure 1. Typical scan of dynamic mechanical properties of Spectra® polyethylene laminate with blended matrix system of polyurethane and vinyl ester .

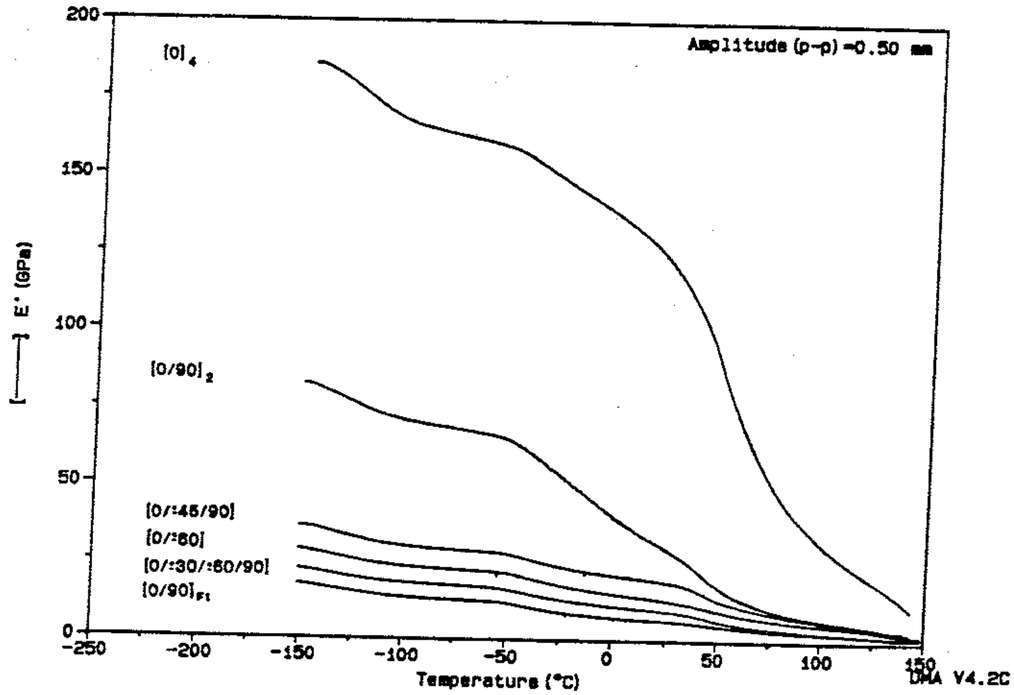


Figure 2. Flexural storage modulus (E') of Spectra® laminates as a function of temperature.

*Table 1. Dynamic mechanical properties of Spectra® laminates. **

Sample ** [Ply Angle]	T_g *** (°C)	$\tan\delta_{Tg}$ (x10³)	E'_{Tg} (GPa)	E''_{Tg} (GPa)	E'_{20} (GPa)
$[0]_4$	-126.4	16.51	177.20	2.93	125.30
$(90)_4$	-122.5	63.10	7.19	0.45	1.36
$[0/90]_2$	-127.8	26.11	76.83	2.01	31.61
$(\pm45)_2$	-127.9	31.13	26.12	0.81	13.58
[0/±45/90]	-124.6	39.29	32.87	1.29	19.60
(45/0/90/-45)	-124.8	53.09	14.28	0.76	8.05
(±22.5/±67.5)	-125.2	39.75	26.31	1.05	14.16
[0/±60]	-123.0	58.33	25.51	1.49	13.55
(60/0/-60)	-122.2	60.48	17.09	1.03	11.73
(±30/90)	-120.6	57.14	18.52	1.06	11.59
[0/±30/±60/90]	-127.1	32.38	20.21	0.07	10.01
(30/0/60/-30/90/60)	-124.0	31.67	21.79	0.07	7.37
(30/60/0/90/-30/-60)	-127.1	37.62	11.56	0.43	5.47
$[0/90]_{F1}$	-116.7	85.71	14.65	1.26	6.77
$(\pm45)_{F1}$	-117.8	85.24	12.52	1.07	5.90
$(\pm45)_4$	-129.6	27.81	16.91	0.47	6.12
$[0/\pm60]_2$	-127.1	52.61	15.94	0.84	5.50
$(60/0/-60)_2$	-128.2	62.38	13.61	0.85	4.90
$(\pm30/90)_2$	-129.2	58.57	12.06	0.71	3.20
$(30/90/-30)_2$	-127.8	50.48	23.05	1.16	5.98
$[0/90]_{F2}$	-123.6	44.76	22.65	1.01	10.63
$(\pm45)_{F2}$	-122.2	42.86	15.21	0.65	6.60

NOTES: * Subscripts Tg and 20 are properties at Tg and at 20 °C, respectively.
** Sample in ( ) indicate alternate test direction for preceding laminate configuration in [ ].
*** Measured by Dynamic Mechanical Analyzer.

The smallest value is demonstrated by the $[90]_4$ laminated sample where the performance appeared to be more influenced by matrix properties than fiber properties. The flexural storage moduli of the fabric laminates are significantly lower than angle-plied laminates. As was expected, the tan δ at T_g is nearly inversely proportional to the flexural storage modulus (Figure 3).

As indicated earlier, the dynamic mechanical properties within a laminate are different depending on test direction, and the final performance of the laminate is a result of the contributions of these varying properties. The relationship of the flexural loss modulus (E") versus the flexural storage modulus (E') for each laminate is plotted in Figure 4. For those configurations where three or more data points (different test directions) are available, the relationship appears linear as was expected based on fundmental viscoelastic behavior of polymeric materials.[4] By

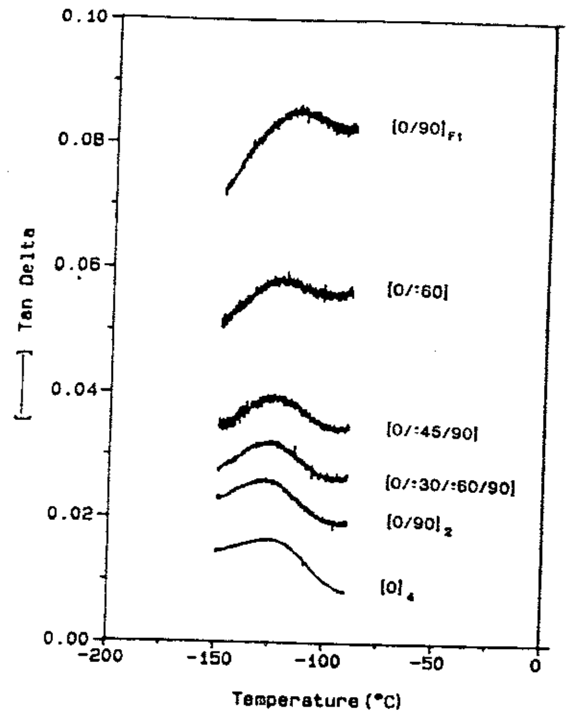


Figure 3. Tan δ at T_g of Spectra® laminates as a function of temperature.

assuming that the linear relationship is true for all laminates examined in this study, average generalized properties are calculated by the following empirical relationship obtained from Figure 4.

$$E'' = \eta E' + C \tag{3}$$

where η is the slope of the E"/E' relationship for each laminate, which represents the average damping behavior. Therefore, η is conveniently termed the energy dissipation factor of the respective laminates and is listed in Table 2.

BALLISTIC RESISTANCE ANALYSIS

Reasonably significant effects were observed in the ballistic performance of each low areal density angle-plied laminate examined in this study. However, due to classification restrictions on ballistic data at the higher areal densities, the low areal density data are combined with the high areal density data for discussion of the angle-plied laminates represented by Figures 5, 6, and 7. The significance in ballistic performance of the Spectra® composites at the low areal densities are examined later in Figure 8.

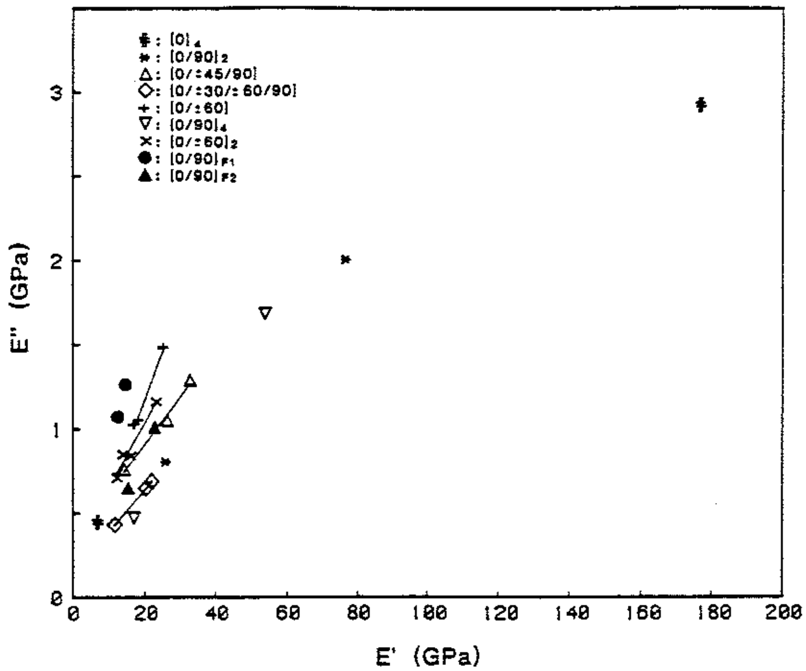


Figure 4. Flexural loss modulus (E") vs flexural storage modulus (E') at T_g of Spectra® laminates. Slopes of each laminate are energy dissipation factor of represented laminates.

Table 2. Relation Between Energy Dissipation Factor, η, Obtained From Equation 7 and Kinetic Energy Absorption Efficiency (KE/AD) of Spectra® Laminates Upon Ballistic Impact.

Sample Identification	η	KE/AD
$[0]_4$	0.0146	17.95
$[0/90]_2$	0.0237	21.16
$[0/\pm45/90]$	0.0280	18.09
$[0/\pm60]$	0.0568	22.31
$[0/\pm30/\pm60/90]$	0.0233	16.23
$[0/90]_4$	0.0329	20.39
$[0/\pm60]_2$	0.0383	21.83
$[0/90]_{F1}$	0.0892	30.14
$[0/90]_{F2}$	0.0481	26.43

The ballistic limits (BL) as a function of areal densities (AD) are plotted in Figure 5 using an empirical relationship as follows:

$$BL = a\,(AD)^b \tag{4}$$

A similar relationship was reported by Song et al. for Kevlar® and S-2® glass laminate studies.[12] In this case, both a and b are constants and are included in Figure 5. An interesting observation in this figure is that at low areal density, both Spectra®-based laminates demonstrate similar ballistic limits. However, as areal density increases, differences in ballistic limits become more apparent, with the Spectrashield®-based composites showing higher results. This trend is supported by ballistic test data generated at areal densities typical of personnel armor applications, which show Spectrashield®-based composites demonstrating significantly better ballistic impact penetration resistance than the Spectra® fabric-based composites.[3]

The specific ballistic resistance efficiency, described as BL/AD, are plotted as a function of areal density in Figures 6 and 7. As illustrated, the ballistic-resistance efficiency decreased as areal density increased (Figure 6). As indicated in Figure 7, the rate of reduction of ballistic resistance efficiency is greater on fabric-based laminates than on the Spectrashield®-based composite. The relation obtained from data plotted in Figure 7 is represented by:

$$\ln (BL/AD) = \ln c - d \ln (AD) \tag{5}$$

where c and d are constants.[12]

Figure 8 is a plot of the energy dissipation factor, η, against kinetic energy absorption efficiency of the laminates (KE/AD). Although some scatter in the data is shown, proportionality between KE/AD and η is observed. This result suggests that the damping properties at the low temperature (-125 °C) transition, which happens to be the T_g of polyethylene, can be useful in predicting the potential for high-speed impact resistance capabilities in laminated composites.

FAILURE MECHANISM ANALYSIS

As indicated by Laible and others, the mode of failure can be diverse in composites materials.[15-18] Failure may occur through one mechanism acting alone or through a combination of different mechanisms, such as shear or fiber cutting, tension or fiber breaking, fiber debonding, fiber pull out, delamination and matrix failure. Visual examination of the ballistically impacted Spectra® composites suggests a variety of failure mechanisms occurred in the

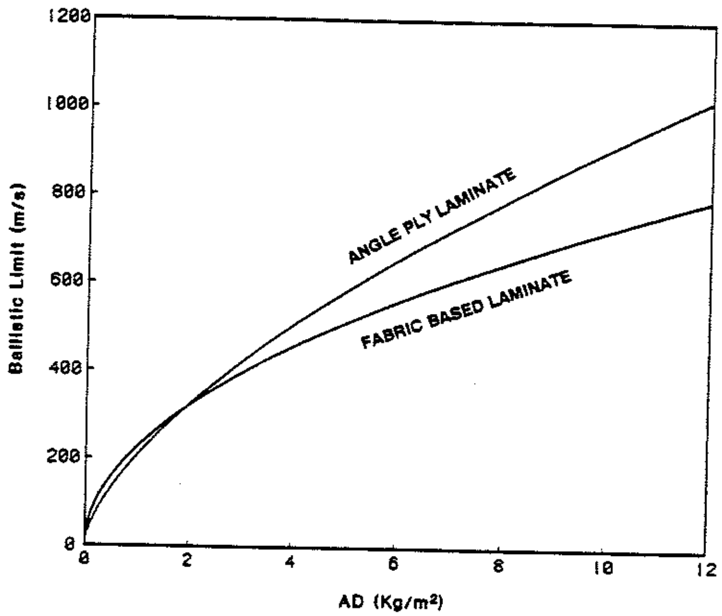


Figure 5. Ballistic limit of Spectra® laminates as a function of areal density. Constants a and b for angle plied and fabric-based laminates are 205.36, 0.65 and 226.36, 0.51 respectively.

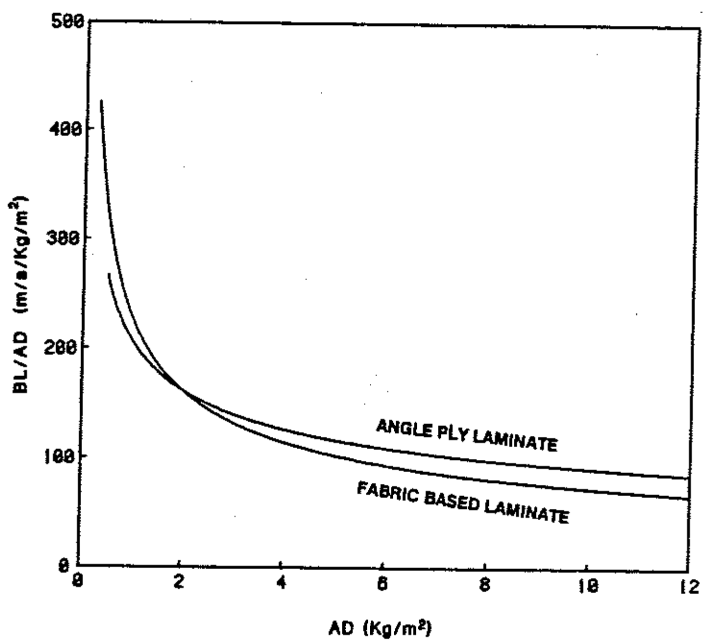


Figure 6. BL/AD vs areal density of Spectra® laminates.

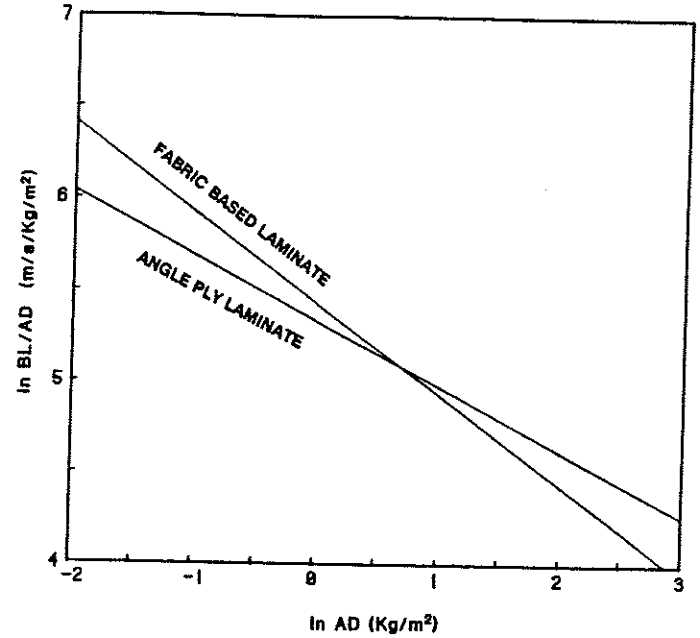


Figure 7. Logarithmic expression of Figure 6. Slopes, which are the reduction rate of ballistic resistance efficiency for angle-plied and fabric-based laminates are (0.35) and (0.49) respectively.

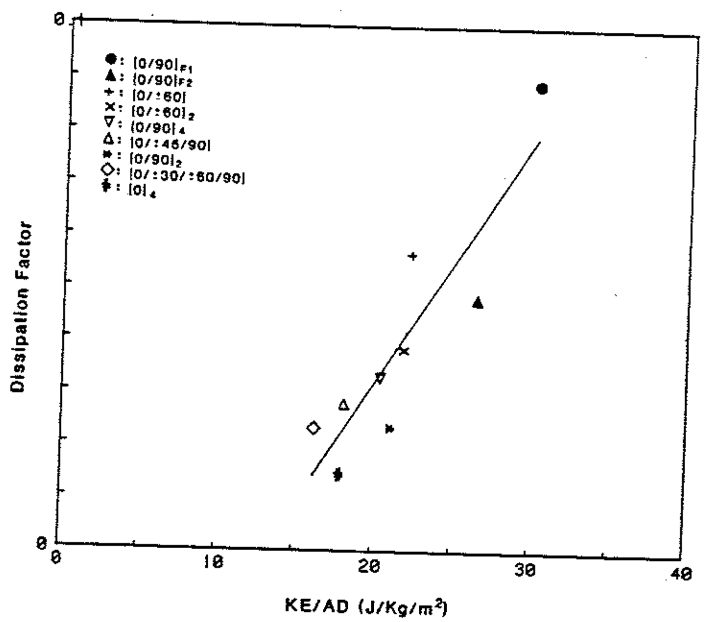


Figure 8. Dissipation factor, η, as a function of KE/AD on various angle-plied and fabric-based laminates.

Spectra® fabric-based composites as well as in the Spectrashield® angle-plied laminates. The Spectra® fabric-based composites show evidence of failure very typical of that reported in other fabric-based composites systems. Specifically observed is delamination in a symmetrical, out-of-plane cone shape around the impact point, with fibers apparently failing due to shear or fiber cutting in the early layers of the composite and in tension at the rear of a completely penetrated panel.[2,17]

The delamination pattern of the Spectrashield® angle-plied laminates appears to be different than that demonstrated in the fabric-based systems. The delamination in the Spectrashield® laminates more closely suggests the generator strip phenomenon reported by Ross et al.[18] That is, upon impact, the projectile pushes a strip of the first layer of the laminate toward the rear of the panel. The length of that strip is considered to be somewhat dependent upon the amount of time required for the projectile to cut through the first layer; the width of the strip usually correlates to the diameter of the projectile. The first strip of the delamination, in turn, applies a transverse load to the second ply and generates delamination successively through the remaining layers of the laminate until penetration occurs or the projectile is stopped. As shown in Figures 9a and b, the delamination failure that occurs in the Spectrashield® angle-plied laminate appears to approximate that phenomenon and each configuration tends to follow the angle of the respective fiber orientation in the panel.

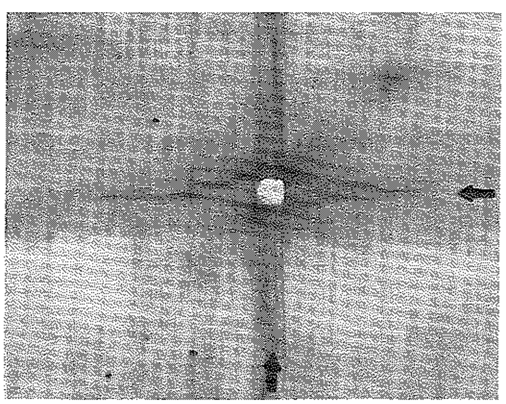


Figure 9a. Delamination pattern of [0/90] Spectrashield® laminate

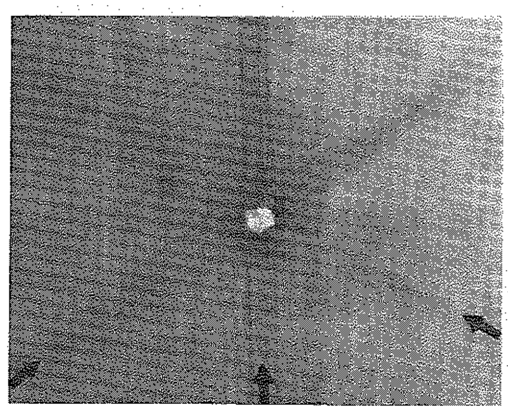
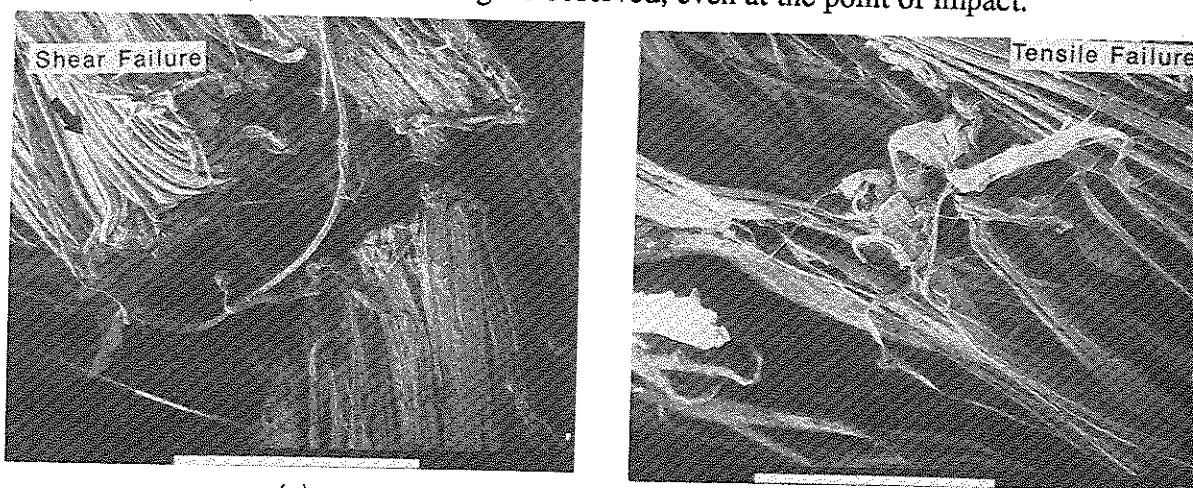


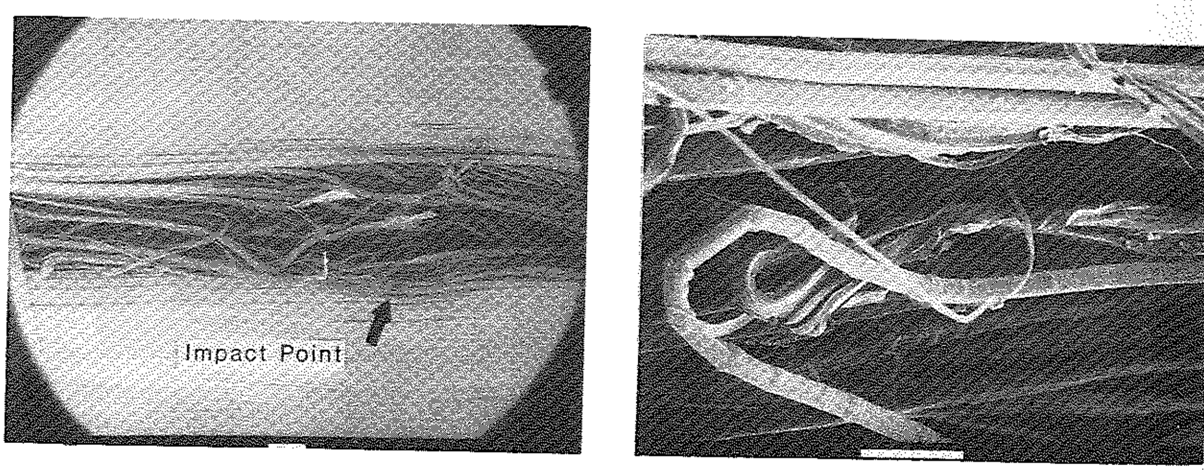
Figure 9b. Delamination pattern of [0/±60] Spectrashield® laminate.

Inspection through scanning electron microscopy of the Spectrashield®composites indicates that fibers experiencing the initial impact in the angle-plied panels fail in shear or from fiber cutting (see Figure 10a, showing the impact area of the [0/±60] sample). In those cases where fiber damage was visible in the back layers of the laminate, such as in the [0/±60] sample, the mode more closely resembled tensile failure (Figure 10b). Many of the laminates appear to allow the test projectile to penetrate by moving fibers laterally or through fiber pull out rather than straining the fibers to break. This was particularly true, as illustrated in Figure 11, of the $[0]_4$ sample, where very little fiber damage is observed, even at the point of impact.



(a) (b)

Figure 10. Ballistic failure mode of Spectrashield®[0/±60] laminate at impact point; (a) face of panel - 45X magnification; (b) back of panel - 45X magnification.



(a) (b)

Figure 11. Ballistic failure mode of Spectrashield®$[0]_4$ laminate at impact point; (a) face of panel - 6X magnification; (b) back of panel - 200X magnification.

The lack of significant fiber breakage in the Spectrashield®angle-plied laminates at the low areal densities is likely responsible for the reduced energy absorption efficiencies compared to the woven fabric-based laminates at similar areal densities (see Table 2). Spectrashield® laminates at much higher areal density do demonstrate some of the same failure mechanisms. The generator strip delamination is less observable in thicker samples; however, substantial delamination does occur. Considerable fiber pull out is also evident in panels at areal densities equivalent to helmet weights.

The photomicrographs included in the preceding discussion show some melting at the point of rupture in the Spectra®fibers that underwent ballistic impact. In this study, no attempt is made to determine if the apparent melting occurs as a result of friction generated during the impact event or if it is a post-impact phenomenon. That discussion, alone, could be the topic for several additional papers on the Spectra®-based composites, whether fabric-based or unidirectional-based materials.

CONCLUSIONS

Dynamic mechanical analysis revealed that the effect of fiber orientation within the Spectrashield®composite is significant. Composites with fiber alignment along the test direction show higher stiffness with lower damping than those with fiber orientation away from the test direction. Low temperature transition (T_g of polyethylene) observed at -125 °C is considered to be an important behavior in regard to ballistic impact resistance since the behavior of viscoelastic material at high strain rates, such as ballistic impact, is similar to the behavior at very low temperature.

A generalized average energy dissipation factor, η, was obtained from the relation of flexural storage and flexural loss moduli at the T_g of polyethylene, which was recorded from several testing directions within an angle-plied composite. Relations between the generalized average energy dissipation factor, η, and the kinetic energy absorption efficiency upon ballistic impact show reasonably good agreement. This fact suggests that the damping behavior of polyethylene at the low temperature transition is another important parameter contributing to the excellent ballistic impact resistance of Spectrashield®composites.

At very low areal density, both Spectra®-based composites appeared to demonstrate similar ballistic resistance performance; at higher areal denisty, the Spectrashield®angle-plied composite showed an advantage. Among the angle-ply composites, the [0/±60] laminates gave the highest performance followed closely by $[0/90]_2$, and then the $[0/\pm45/90]$, $[0]_4$ and $0/\pm30/\pm60/90]$. As areal density increases, ballistic resistance efficiency dropped rapidly. The rate of decline for the fabric composite was faster than for the angle-ply laminate. Multiple failure mechanisms and delamination modes were observed in the Spectra® composites. In either composite (fabric-based or the Spectrashield®based), fiber failure appeared to be caused by transverse shear on plies near the impact face and by axial tensile failure or pull out at the exit point. Evidence of extensive strain wave propagation was observed on both the front and back of the laminates as was melting in the impacted fibers.

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